THE SATELLITES IN THE SOLAR SYSTEM

By Seth B. Nicholson

The satellites of the solar system have made several important contributions to our astronomical knowledge. Perhaps their greatest achievement is in furnishing the most accurate means of weighing the planets. The discovery of the velocity of light resulted directly from the study of their motions and in many cases they have furnished the incentive for valuable research; but aside from any contribution to the larger problems of astronomy they will always be of interest as individual members of the solar system.

The principal data concerning the various satellites are presented in tabular form. The mean distance from the center of the primary is given in units of one thousand miles. For comparison the equatorial radii of the planets in miles and their sidereal periods are also included. The stellar magnitude is in general the mean visual magnitude reduced to the distance of the primary from the Earth at mean opposition, but the starred values for the faint satellites are photographic. In obtaining g, which is the visual magnitude that the satellite would have if at full phase and unit distance from the Earth and Sun, a color index of +0.8 has been used. The factor p, which is closely related to the albedo, is defined by Russell in the *Astrophysical Journal* for April, 1916. Except where starred, p is an assumed value. The diameters and magnitudes for *Titan* and the four large satellites of *Jupiter* are those adopted by Russell. The other diameters, except that of the Moon, have been computed using the formula $\log_{10}$ diam. (in miles) $= 2.92 - 1/5\, g - \log_{10} \sqrt{p}$. (An error of 0.05 in the value of p introduces an error of about 10% in the estimated diameters.) The estimated magnitudes of *Saturn's* satellites as given by Barnard make these objects from one to two magnitudes fainter than the photometric values given here. This difference, which is doubtless due in part to the nearness of the bright planet, gives an idea of the difficulty experienced in observing satellites.

On account of our nearness to the Sun, the Moon is by far the brightest satellite as seen from the surface of its primary. *Jupiter's* satellites are large, numerous, and some of them quite near the planet, but their light on *Jupiter*, even if all were in full phase at once, would be only one-third that of full moonlight on the Earth.

In size, however, several of the satellites exceed the Moon, the two largest being even larger than the planet *Mercury*. For those whose masses are known the densities are as follows: Moon, 3.4; *Jupiter* I, 2.4; *Jupiter* II, 3.1; *Jupiter* III, 2.1; *Jupiter* IV, 1.2; *Titan*, 5.6.

Several observers have seen indications of markings on the four large satellites of *Jupiter*. *Jupiter* I is most consistently seen as brighter at the poles than at the equator and this seems to be the best authenticated case of surface markings on any of the satellites other than our Moon. Soon after its discovery *Iapetus* was found to vary in magnitude, being always brighter at western than at eastern elongation. The variation is about 1.7 mag. This is generally explained by assuming that the satellite always keeps the same face toward *Saturn* and that its surface is very uneven in brightness.[1] Several of the other satellites have been observed to vary, and in most cases the same explanation is plausible.

The motions of the satellites offer some very interesting problems in the study of the evolution of the solar system. *Phobos* is the only known case of a body revolving about its primary faster than the primary rotates on its axis. As seen from *Mars*, *Phobos* would therefore rise in the west and set in the east. The Moon and all the close satellites of *Mars*, *Jupiter*, and *Saturn* revolve in the same direction as the planets rotate. All of the satellites of *Uranus* move in a plane nearly at right angles to the ecliptic, but observations indicate that the planet's rotation is likewise in the same direction. In the absence of observations to the contrary *Neptune* is also assumed to rotate in the direction of revolution of its satellite, which, however, is retrograde. *Phoebe*, the outermost satellite of *Saturn*, and *Jupiter* VIII and IX are the only positive examples of a retrograde motion with respect to the primary's rotation. Most of the satellites move in nearly circular orbits almost in the plane of their planet's equator. The striking exceptions to this rule are the outer satellites of *Jupiter* and *Saturn*. This seems to require for them a theory of origin or evolution different from that of the inner satellites.

A very interesting theory has been advanced by W. H. Pickering to account for the retrograde motions of these outer satellites. He assumes that the evolution of the solar system has been along the

[1]If we assume $p = 0.10$ for the faint side, the bright side would have $p = 0.53$. The corresponding value for the mean magnitude is $p = 0.23$. These large and small values are near the extreme limits of the observed value of p for other satellites. The assumed value for *Iapetus* at its mean magnitude, therefore, cannot be changed much without necessitating an unreasonable value for the bright or dark face.

lines indicated by a nebular hypothesis and that when a planet is first formed its rotation is retrograde. In the early stages the outer satellites were formed. Then they were direct moving objects referred to the primary's rotation. Due to a tidal action between the planet and the Sun the direction of rotation of the planet has been reversed, leaving the old satellites as they were. This reversal came about by a change in the inclination of the planet's equator, which has turned completely over so that what is now its north pole was formerly the south pole. The direct moving satellites were formed, according to the theory, after this reversal had taken place. *Jupiter* VI and VII are, however, direct moving objects, with large eccentricities and inclinations, and at about the same distance from the primary as *Phoebe*. The more generally accepted theory is that the outer satellites, at least, have been acquired by capture, while the others have been formed in the regular evolution of the planetary system.

The four distant satellites of *Jupiter* form two very similar pairs. *Jupiter* VI and VII have nearly equal periods, similar eccentricities, and at present their perijoves lie in opposite directions from *Jupiter*. Their orbit planes, while having inclinations similar in magnitude, are by no means coincident. The same relations hold for the motions of *Jupiter* VIII and IX. Since there is no known reason why these particular periods should be more stable than any other, a common origin is indicated for the members of each pair. This would seem to be opposed to the theory that they were captured, at least as individuals. Another interesting fact is that the two satellites differ in brightness by almost the same amount in each case.

The outer satellites are so far from their primaries that the perturbative action of the Sun is very large. In fact it may be shown that if it were not for their retrograde motions *Jupiter* VIII and IX could not be permanently held by *Jupiter*. The orbit of an object at the distance of *Phoebe*, however, would be stable even if its motion were direct. Perturbations change the orbits so much that it is almost impossible to think of them in the ordinary sense. For instance, the eccentricity of *Jupiter* VIII has been known to change from 0.50 to 0.23 during two revolutions of the satellite.

Many observers have searched carefully in the neighborhood of the planets for additional satellites. Thus far *Mercury* and *Venus* remain the only planets with no known attendants. At least two

observers have reported a satellite for *Venus*, but the observations were never confirmed and are now thought to have been in error. W. H. Pickering found a 17th magnitude object, apparently a satellite of *Saturn*, on plates taken in 1904 and another on plates taken in 1900. Orbits were computed for each of the objects. The periods were the same, about 21 days, but otherwise the orbits could not have referred to the same object unless the perturbations of *Titan*, which was not far away, could have been responsible for the great changes. At later oppositions the positions indicated by both orbits have been searched carefully with no success, so that while a tenth and even an eleventh satellite of *Saturn* may have been observed its present orbit and position are unknown.

Neptune and *Uranus* are so far away that their satellite field could be covered by a single photograph with a large reflector so that it is fairly safe to say that they have no additional satellites as bright as 17 or 18 magnitude, unless they are hidden in the glare of the planet. The same conditions apply to *Mars*, whose satellite field is actually small on account of the small mass of the planet. In the case of *Jupiter* and *Saturn*, however, the distance at which a satellite might be found is very large. *Jupiter* VIII and IX, for instance, may be as far as three degrees from the planet. The motion of an outer satellite may be so nearly like that which an asteroid might have that its identification necessitates a fairly long series of observations. Many observers have found moving objects in the neighborhood of *Jupiter*, but the observations have been too few to decide whether they are satellites or asteroids. *Jupiter* VI is fairly bright, much easier to see than *Jupiter* V, and the only reason it escaped detection so long was on account of its great distance from the planet. It is quite possible, therefore, that *Saturn* and *Jupiter* have more satellites fainter than the 16th magnitude.

SATELLITES OF THE SOLAR SYSTEM

Name	Mean Distance in Thousands of Miles	Sidereal Period		Stellar Magnitude	g (Absolute Magnitude)	p	Diameter in Miles	Discoverer	Date
				THE EARTH $\begin{cases} 3{,}963 \text{ miles} \\ 23^h56^m \end{cases}$					
The Moon	239	27^d	8^h	-12.6	$+0.4$	0.10*	2160		
				MARS $\begin{cases} 2{,}274 \text{ miles} \\ 24^h37^m \end{cases}$					
Phobus	5.8		8	+12.5	+13.0	0.13	7	Asaph Hall	1877
Deimos	14.6	1	6	+12.8	+13.3	0.13	5	Asaph Hall	1877
				JUPITER $\begin{cases} 45{,}128 \text{ miles} \\ 9^h55^m \end{cases}$					
V	113		12	+13.	+6.	0.15	150	Barnard	1892
I (Io)	261	1	18	+ 5.5	− 1.2	0.46*	2110	Galileo	1610
II (Europa)	415	3	13	+ 5.7	− 1.0	0.51*	1870	Galileo	1610
III (Ganymede	664	7	4	+ 5.1	− 1.6	0.30*	3270	Galileo	1610
IV (Callisto)	1167	16	18	+ 6.3	− 0.4	0.11*	3140	Galileo	1610
VI	7400	266	00	+13.7	+ 7.0	0.15	90	Perrine	1904
VII	7600	276	16	+17. *	+ 9.	0.15	35	Perrine	1905
VIII	14600	739		+17. *	+ 9.	0.15	35	Melotte	1908
IX	14800	750		+18.6*	+11.1	0.15	15	Nicholson	1914

SATELLITES OF THE SOLAR SYSTEM (Continued)

Name	Mean Distance in Thousands of Miles	Sidereal Period		Stellar Magnitude	g (Absolute Magnitude)	p	Diameter in Miles	Discoverer	Date
				SATURN $\begin{cases}\text{38,228 miles}\\ 10^h14^m\end{cases}$					
Mimas	117		23	+12.1	+ 2.5	0.20	600	W. Herschel	1789
Enceladus	157	1	9	+11.6	+ 2.0	0.20	750	W. Herschel	1789
Tethys	186	1	21	+10.5	+ 0.9	0.25	1110	J. D. Cassini	1684
Dione	238	2	18	+10.7	+ 1.1	0.25	1010	J. D. Cassini	1684
Rhea	332	4	12	+10.0	+ 0.4	0.25	1400	J. D. Cassini	1674
Titan	771	15	23	+ 8.3	− 1.3	0.33*	2670	Huygens	1655
Hyperion	934	21	8	+12.9	+ 3.3	0.20	410	G. P. Bond	1848
Iapetus	2225	79	22	+10.9	+ 1.3	0.25	930	J. D. Cassini	1671
Phoebe	7300	523	16	+17. *	+ 7.	0.15	90	W. H. Pickering	1898
				URANUS $\begin{cases}\text{15,097 miles}\\ 11^h\end{cases}$					
Ariel	120	2	12	+15.	+ 2.	0.25	650	Lassell	1851
Umbriel	167	4	3	+15.	+ 2.	0.25	650	Lassell	1851
Titania	273	8	17	+14.5	+ 1.8	0.25	750	W. Herschel	1787
Oberon	365	13	11	+14.7	+ 2.0	0.25	650	W. Herschel	1787
				NEPTUNE $\begin{cases}\text{17,412 miles}\\ \text{Unknown}\end{cases}$					
(Nameless)	222	5	21	+13.6	− 1.1	0.33	2430	Lassell	1846